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Essential Spawning Habitat for Atlantic Sturgeon in the James River, Virginia.

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ESSENTIAL SPAWNING HABITAT FOR ATLANTIC STURGEON IN THE JAMES RIVER, VIRGINIA

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Environmental Studies at Virginia Commonwealth University.

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Abstract

ESSENTIAL SPAWNING HABITAT FOR ATLANTIC STURGEON (*Acipenser oxyrinchus*) IN THE JAMES RIVER, VIRGINIA

By Geoffrey C. Austin, B.S.

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Environmental Studies at Virginia Commonwealth University.

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Director: Greg Garman, Ph. D., Center for Environmental Studies

Substrate composition plays a critical role in determining the spawning success of Atlantic sturgeon. A benthic analysis of the tidal freshwater portion of the James River, Virginia, was performed to locate and protect remaining sturgeon spawning habitat within the James River system. I modeled structural habitat, substrate distribution, and river bathymetry from Richmond, Virginia to the Appomattox River confluence. A classification model was developed to describe the dominant substrate type (mud/silt, sand, gravel, bedrock) using side scan sonar data collected from August 2011-Febuary 2012. River depth, bottom imagery, substrate density (hardness), and ground truth substrate samples were interpolated into a GIS model to spatially describe and quantify essential sturgeon spawning habitat. Finally, I attempted a change analysis of historical substrate composition throughout the study area. Gravel, cobble, and bedrock, swept clean of silt or mud, was deemed a hard bottom substrate suitable for spawning success.

Mud and silt dominated the vast majority of river substrate, representing approximately 67 % of river bottom surveyed. Sand comprised 17 % of river bottom, gravel represented 11 % and bedrock represented 5 %. Sixteen percent of the reach was hard bottom habitat consisting of a bed substrate dominated by gravel, cobble, or bedrock. Regions of hard bottom habitat found at depths ≥ 10 m were selected to model essential sturgeon spawning habitat. The river bottom within the reach contained approximately 8 % essential spawning habitat. The majority of hard bottom habitat was located in major bends of the river where scouring occurs. The historical comparison of available hard bottom habitat identified a 28 % loss of hard bottom since 1853. The greatest losses in hard bottom occurred in the upper portions of the study area (55 % loss in hard bottom habitat). Hard bottom habitat lost in the lower portion of the study area was partially offset by the creation of new hard bottom habitat within the narrow channel cuts bypassing Jones Neck and Turkey Island. Historical comparison of the Hatcher Island, Turkey Island, and Jones Neck oxbows identified heavy siltation and reduced depths likely due to anthropogenic alterations in the meander bends linked to shipping channel creation. The altered flow regime has resulted in increased sedimentation and has drastically reduced available hard bottom substrate within the natural channel of Jones Neck and Turkey Island. The increased availability of hard bottom habitat within the confines of the shipping channel has indicated that the alteration of the river bottom, through flow modification and dredging practices, may have replaced a portion of lost historical spawning habitat. Fisheries managers could use the data from the substrate analysis to better understand and protect essential areas necessary for Atlantic sturgeon spawning success.

INTRODUCTION

Sturgeons (Acipenseridae) comprise 27 living species (Birstein and Bemis 1997) that occur in lakes, rivers, and coastal waters throughout North America and Eurasia. Sturgeons are one of the oldest fish species alive today. Historically, nine sturgeon species were native to waterways along North America's coastline, from the Gulf of Mexico to Newfoundland, in the Great Lakes and the St. Lawrence, Missouri, and Mississippi Rivers, and from California to British Columbia (Cech and Doroshov 2004, Bemis and Kynard 1997). Throughout this once extensive range, most sturgeon populations are presently considered highly threatened or vulnerable to extinction (Birstein et al. 1997). During the early 20th Century, overharvest caused wide-spread declines in sturgeon abundance (Bain et al. 2000). Due to the late maturity of sturgeon, migration patterns, and sensitivity to environmental stressors, many populations are under threat from poaching, overfishing, water pollution, and habitat loss. (Collins et al. 2000b, Secor et al. 2000, Kahnle et al. 1998). In estuarine and freshwater habitats, threats to sturgeon include habitat degradation and loss from dredging, impediments, and poor water quality (Bushnoe and Musick 2005). Currently, seven of the nine sturgeon species native to North America are federally listed as threatened or endangered (USFWS 2012).

Atlantic sturgeon (*Acipenser oxyrinchus*) is capable of growing to approximately 4.3 m in length and weighing up to 370 kg (Scott & Crossman 1973). They are bluish-black and brown with pale sides and a white belly with five major rows of dermal scutes. Atlantic sturgeon were once abundant in major coastal rivers along the Atlantic slope of North America from Hamilton Inlet, Labrador to the St. John's River, Florida (Birstein et al. 1997, Murawski and Pacheco 1977, ASMFC 1990). Atlantic sturgeon are benthic feeders and typically forage on invertebrates including amphipods, isopods, shrimps, and mollusks (Secor et al. 2000). As the sturgeon roots along the bottom, mud, plant material, sludge worms, chironomid, mayfly larvae, isopods, amphipods, and small bivalve mollusks are often consumed (Scott and Crossman 1973). Like adults, juveniles feed along the bottom sucking in material through a ventral, protractile mouth and consume a variety of plant and animal material (Secor et al. 2000).

Atlantic sturgeon are anadromous, with spawning adults migrating upriver in spring, beginning in February-March in the south, April-May in the mid-Atlantic, and May-June in Canadian waters (Smith 1985, Smith and Clugston 1997). The James River and other southern rivers, such as the Cape Fear River in South Carolina, may experience an additional spawning migration in the fall (Balazik et al. 2012, Smith 1985, Collins et al. 2000a). The Atlantic sturgeon spawning interval is estimated at 1-6 y depending on sex (Van Eenennaam et al. 1996, Bain 1997, Simpson and Fox 2007). Atlantic sturgeon spawn on gravel, rocks, rubble, and hard structure such as boulders or exposed bedrock in fast flowing sections of river containing eddies or other current breaks (Smith 1985, Bushnoe and Musick 2005). Eggs of Atlantic sturgeon are adhesive and demersal. The eggs remain on the river bottom in deep channel habitats attached to hard bottom substrate (Smith et al. 1980). Sturgeon spawning beds must be dominated by exposed hard substrate $\geq$ 30 mm in size (Sulak et al. 2000). The hard substrate must stay free of fine substrate such as silt, clay, mud, or sand in order for deposited eggs to develop. Spawning sturgeon within the James River have not been documented but successful spawning is inferred through the observation of young of the year. Fecundity of female Atlantic sturgeon can range from 400,000 to 8 million eggs, resulting in large-scale broadcasting of eggs, maximizing the chance of a successful spawn. (Simpson and Fox 2007, Dadswell 2006, Smith et al. 1980, Van Eenennaam et al. 1996, Smith 1985).

Little information is known about the early life stages of Atlantic sturgeon. Larval Atlantic sturgeon emerge after roughly 4-6 d and remain near the tidal freshwater spawning habitat, gradually extending downstream as the juveniles grow and attain the ability to tolerate brackish water (Bain et al. 2000, Smith et al. 1980). Atlantic sturgeon larvae are capable of swimming immediately, and tend to reside in regions of a river with a gravel substrate for the first few days of life (Smith 1985, Gessner et al. 2009). Larval Atlantic sturgeon are reported to be darkly pigmented and be active swimmers, capable of swimming throughout the water column (Smith et al. 1981). Approximately 9 to 10 d after hatching, the yolk sac is absorbed and the larvae exhibit benthic behavior (Smith 1985). Upon reaching 1-6 y in age, Atlantic sturgeon leave estuaries and enter ocean waters, residing frequently above gravel and sand substrate types (Smith 1985, Bain 1997, Stein et al. 2004). About 10 y after entering oceanic waters, juvenile Atlantic sturgeon reach adult size (Bain 1997). The Atlantic sturgeon matures slowly; with females reaching sexual maturity at 16 y or older and males at 12 y or older within the mid-Atlantic coast region (Van Eenennaam et al. 1996). Atlantic sturgeon often undertake long-distance migrations along the Atlantic coastline between spawning events (Bain 1997, Smith and Clugston 1997). The accepted maximum age for the species is approximately 60 y (Scott and Crossman 1973).

Genetic evidence and observation of sturgeon young in the James River supports the existence of a Chesapeake Bay haplotype, indicative that spawning still occurs in the Chesapeake Bay region (King et al. 2001). Based on fisheries by-catch and population monitoring data, Atlantic sturgeon travel through the Chesapeake Bay in April and May on their way to spawn (Welsh et al. 2002). Historically, in the Chesapeake Bay, Atlantic sturgeon likely spawned in the tidal freshwater region of most major tributaries connected to the bay. Currently spawning is confirmed only in the James and York River systems (Bilkovic et al. 2009, Welsh et al. 2002).

Given the widespread decline in Atlantic sturgeon populations, the Atlantic States Marine Fisheries Commission (ASMFC) initially produced a Fishery Management Plan for the Atlantic sturgeon with a stated goal of restoring the species throughout its range to allow an annual harvest of 317 metric tons, which was approximately 10 % of the peak catch totals (Smith and Clugston 1997). In 1998, the ASMFC instituted a coast-wide moratorium on the harvest of Atlantic sturgeon. In 2012, the National Oceanic and Atmospheric Administration (NOAA) listed Atlantic sturgeon as Endangered based on five distinct population regions along the U.S. East coast (ASMFC 1998). Even though there is no allowable commercial, recreational, or tribal harvest in the United States, the fishing moratorium has not been in place long enough to generate a measurable recovery (Auer 2004, Simpson and Fox 2007). Due to a lack of published studies pertaining to the James River sturgeon spawning habitat, effective Atlantic sturgeon management decisions have not been clearly defined for the James River system.

The endangered species listing for Atlantic sturgeon population spawning in the James River and Chesapeake Bay area has made identification and protection of the remaining spawning habitat a restoration priority. Atlantic sturgeon spawning has historically occurred between the City of Richmond and the City of Hopewell, in waters < 0.5 ppt salinity (Bain et al. 2000, Sulak et al. 2000, Van Eenennaam et al. 1996). River bottom composition in this reach has never been thoroughly characterized and has been significantly altered from its historical channel profile through dredging practices (Diaz 1989). In 1843, significant removal of hard substrate occurred just downstream of Richmond in order to accommodate increased shipping activity. Construction of a 7.6 m-deep shipping channel in 1854 altered the natural flow path of the river to bypass shallow shoals, and is currently maintained by the U.S. Army Corps of Engineers (Holton and Walsh 1995). The shipping channel resulted in the creation of the Turkey Island, Jones Neck, and Dutch Gap channel cuts (Figure 1), which significantly altered the historical flow and substrate composition of the river (Bushnoe and Musick 2005). Downriver of Hopewell, mud becomes the primary bottom type in the main channel with sand becoming more common near the mouth of the river. Downriver of Hopewell can also experience seasonally saline or brackish waters in the fall, potentially reducing the spawning viability of any hard bottom habitat downstream of the city (Nichols et al. 1991).

Essential sturgeon spawning habitat in a river system is characterized by a combination of water quality variables such as dissolved oxygen, temperature, water velocity, salinity, depth, and suspended sediment, along with the presence of hard bottom substrate (Niklitschek and Secor 2005, Bilkovic et al. 2009, Collins, et al. 2000a, Diaz 1989, Fox et al. 2000). An elevated nutrient load and high levels of siltation have significantly altered river habitat and species diversity within the tidal freshwater region of the James River (Diaz 1989), although nutrient and sediment loads in the James River have not signifiantly fluctuated in recent years (Langland et al. 2006). Prior observations have indicated the James River rarely experiences low dissolved oxygen (DO) levels and I hypothesize that DO is not likely a factor limiting spawning success (Bukaveckas et al. 2011, Kuo and Neilson 1987). As such, I hypothesize that loss of hard bottom habitat, due to channel alteration and increased sediment load, is the primary factor currently limiting Atlantic sturgeon spawning success and population recovery within the tidal freshwater James River. Since the creation of the shipping channel, areas within the tidal freshwater reach have experienced both recent shoaling and scouring (Holton and Walsh 1995). The extent of habitat alteration and degradation has never been fully assessed. Given the inherent difficulties associated with observing and characterizing spawning locations, a large-scale study covering the full extent of potential spawning habitat was necessary in order to accurately represent the benthic conditions of the river system. Understanding the extent of available spawning habitat should help fisheries managers make effective management decisions that promote the protection and restoration of the Atlantic sturgeon spawning population in the James River.

The primary objective of the study was to characterize and map the benthic habitat in the tidal freshwater reach of the James River in order to quantify and geo-reference essential spawning and early life history habitat for Atlantic sturgeon. A secondary objective of our study was to perform a percent change analysis of substrate data representative of historical conditions within the study area. Specifically, I evaluated the hypothesis that essential Atlantic sturgeon spawning habitat has been significantly reduced in the James River compared to historical conditions, and as such is a primary factor limiting Atlantic sturgeon recovery and spawning success in the Chesapeake Bay area.

STUDY AREA

The James River is formed by the confluence of the Jackson and Cowpasture rivers and flows 368 river kilometers (rkm) to the Fall Line at Richmond, Virginia. The tidal James River Estuary extends 177 rkm from Richmond, Virginia to the Chesapeake Bay (Smock et al. 2005). For the purpose of the study, the tidal freshwater region of the James River is defined as an approximately 60 rkm stretch from Richmond, below the fall line, to the mouth of the Appomattox River near Hopewell, Virginia (Figure 1). Land use in the river basin varies considerably from the headwaters to the mouth. Approximately 71 % of the land is forested, 23

% is agriculture, and 6 % is urban (Bushnoe and Musick 2005). River morphology of the tidal freshwater region of the James River consists of a channelized mainstream along with three large oxbows experiencing significant historical flow alteration due to the creation of shipping channel cuts, bypassing the Jones Neck, Hatcher, and Turkey Island oxbows.

METHODS

Side scan sonar techniques were used to map substrate hardness and bed composition in the tidal freshwater reach of the James River. Prior research indicated that bathymetric side scan sonar is a viable method to survey bottom structure and bed composition (NOAA 2009, Jacobson et al. 2007). Bathymetric mapping of surficial habitat was accomplished through the use of a boat-mounted geo-referencing side scan sonar transducer. Data were collected using a Humminbird 998c SI side scan sonar unit (Humminbird, Inc., Eufaula, AL, USA) positioned directly below a GPS receiver mounted on the port side of the research vessel. The transducer was positioned approximately 0.5 m below the water surface and adjusted in the sonar unit to represent the actual water surface-to-bottom depth. Water surface-to-bottom depth measurements were validated using a weighted tape. A real time data feed to an onboard computer ensured a consistent sampling pattern for the data collection. Post processing of depth, hardness, and side scan sonar imagery data was accomplished using Dr. DepthPC and ArcMap Ver. 9 (Pelin 2011, ESRI 2011). Data collection started just downstream of the City of Richmond and preceded approximately 60 rkm downstream to the mouth of the Appomattox River. Side scan sonar data collection took place from August 9, 2011 until February 27, 2012.

Ground truth data were collected via Ekman dredge substrate samples to statistically define the signal range for each substrate type. The substrate samples aided in the development and validation of a substrate classification scheme. Due to the lack of known spawning locations in the James River, prior research and observations of spawning depths of Atlantic sturgeon within the Hudson, Delaware, and St. Lawrence River systems was used to more clearly define essential habitat depth requirements for Atlantic sturgeon. In order to better understand how substrate composition throughout the reach has changed over the past 160 y, total hard bottom habitat was compared to historical sounding and substrate observations from 1853 and 1880. Analyzing the historic percent of hard bottom sounding observations and current percent hard bottom habitat area over a specific area enabled a comparison of historical substrate composition, and indicated which river sections may have historically supported sturgeon spawning success in 1853 and 1880.

Side Scan Imagery

Side scan sonar has the ability to digitally image and record the benthic habitat of the river bottom in large swaths with two separate sonar cones facing to the port and starboard sides of the research vessel. The side scan imagery can be operated on one of two frequencies: 455 kHz or 800 kHz. Operating the side scan imagery at 800 kHz provided a sharper image resolution, but coverage was limited to a total beam width of 130 degrees, restricting the potential coverage based on water depth. For instance, at a water depth of 10 m, coverage would attenuate at approximately 21 m wide in either direction, resulting in the maximum potential bottom coverage of 42 m at 800 kHz. Selecting 455 kHz provided greater bottom coverage with a total beam width of 180 degrees and was capable of full imagery coverage in shallow waters but at a reduced resolution. Prior to data collection, device testing indicated the study would benefit more from the 800 kHz beam for the purpose of identifying river bottom material. The 800 kHz beam was used as the default beam frequency in moderate to deep waters (≥3 m). In shallow waters outside the main channel the narrow 800 kHz beam was not capable of imaging the river bottom effectively. Hence, the 455 kHz beam was used in shallow waters where the 800 kHz beam produced attenuated imagery. Imagery was manually restricted to 23 m per side within the Humminbird unit, providing approximately 50 m of coverage per pass, but was increased to approximately 30 m per side in shallow waters. Real time data analysis and GPS navigation ensured complete coverage of each section of the reach. Bottom imagery was compiled into a series of mosaics with overlapping edges matched to form a continuous image profile of the river bed (Figure 2). Similar side scan sonar mapping has been done before by the U.S. Geological Survey (USGS) in relation to pallid and shovelnose sturgeon habitat in the lower Missouri River, by NOAA in portions of the James River, and in studies pertaining to bottom habitat classification (Jacobson et al. 2007, NOAA 2009, Barnhart et al. 1998).

Depth and Hardness

During the side scan imagery collection, the transducer simultaneously collected river bathymetry and percent signal return (hardness) with the Humminbird transducer, which emitted a narrow, downward-facing 200 kHz acoustic beam. Multiple longitudinal, parallel passes with and against the river flow were taken in order to achieve adequate coverage of the study area. The number of passes required depended on the river width. Each subsequent pass did not exceed 50 m from the previous boat pass. In order in increase data density and address any data voids, a serpentine pattern was followed over the initial parallel passes (Figure 3). The sampling pattern was chosen based on patterns used in prior research (Jacobson et al. 2007, NOAA 2009), and was deemed an effective method for gathering potentially influential data for the hardness/depth readings in a semi-random and time efficient manner. Due to the scale of the study area, a relatively low data density was found to be appropriate to interpolate such a large study area. While there was complete coverage of the river channel with side scan sonar imagery, the depth and hardness data were interpolated or modeled based on the raw track data. Percent of the river bottom represented by raw data was modeled by isolating depth data with the GPS track line, buffered to the software created raster cell size (3m).

Post Processing

Three spatial layers were developed based on data collected by the 200 and 455/800 kHz beams: bathymetric elevation, substrate hardness and bed imagery. Data were exported to Dr. Depth in order to interpolate the raw data into three continuous profile maps of depth, substrate hardness, and bed imagery. Raw depth data were adjusted based on local tidal charts for the river along with a USGS-operated tide gage (#02037705 located at Richmond City Locks, Richmond, Virginia) to correspond with sea level as defined in the North American Vertical Datum of 1988 (NAVD).

The percent return of the signal reflected off the bottom substrate from the downward facing 200 kHz beam was interpreted as bottom substrate hardness for this study following research and interpolation methods developed for the Dr. Depth software package (Figure 4). Soft substrate absorbed and dissipated a large percentage of the sonar signal, whereas a hard substrate reflected a large percent of the signal. As such, a strong sonar return was interpreted in Dr. Depth as a harder substrate compared to a substrate that reflected a weak sonar return

(Jacobson et al. 2007). In order to compare bed hardness with bed substrate classifications, sonar coverage of the entire reach was required. Analysis of hardness values through Dr. Depth required a signal scaling adjustment as stated in the Dr. Depth bottom analysis procedure help document (Pelin 2011). In order to analyze the return data, signal return values for hardness were adjusted to represent a 1 to 100 % potential range. The adjustment value is determined as 100 divided by the maximum return. The resulting number is used in Dr. Depth as a "gain" value to visualize signal strength as relative hardness for the entire reach. Based on the raw data, the hardness scale for the study was adjusted in Dr. Depth for a gain of 0.555. The 0.555 gain value is specific to the study area and would have to be recalculated for data from another water body. An algorithm within Dr. Depth interpolated the data in order to represent the entire channel width (Figure 5). Dr. Depth interpolated the hardness data no further than 25 m in either direction of the raw data track, and interpolated the depth data no further than 50 m. Interpolation was restricted to a manually drawn shoreline data derived from a NOAA navigation chart surveyed in 1969. Shoreline data was artificially restricted within the waterway in hazardous or exceptionally shallow waters, and may not completely represent the shallow mudflats found in the Jones Neck or Turkey Island oxbows. The depth and hardness data were exported to ArcMap and displayed with a 1 m raster cell resolution.

Ground Truth Data

Ground truth data collected for 50 sampling sites were used to determine the classification scheme that was applied to all hardness data in order to map substrate distribution for the entire reach. The adjusted 1-100 % hardness data were classified into four groups (mud, sand, gravel, cobble/bedrock) based on hardness value and corresponding substrate samples taken from 12 random and 38 predetermined sites. Initial selection of the first 25 ground truth sites were chosen to represent the full spectrum of possible signal return values within a control area, representing a portion of river from Dutch Gap to Jones Neck Island. The final 25 sites were chosen in order to more clearly define the signal range and transitions between each substrate classification type. Site selection for the initial 25 locations included 12 sites selected in ArcMap by random selection, and 13 sites selected based on areas of consistent return signal in order in increase the accuracy of substrate samples. The initial 25 sample points indicated that the range of 30 to 55 % hardness value contained the points of transition between each substrate class for the four categories. The sample locations for the final 25 sites were intentionally selected to represent hardness values between 30 and 55 %. These sites were selected to target locations with hardness values that could represent the transition between mud and sand, or sand and gravel, or gravel and bedrock. The final 25 sites were selected based on return consistency and were selected across the entire study area. The side scan imagery for each sample location was examined to determine if the substrate class was confirmed by the imagery.

All 50 substrate sites were sampled in the same manner. Substrate material was sampled 3 times from each location to confirm consistent and accurate sampling of the site. If the substrate was consistent after 2 samples, the third sample was not taken and noted as such. The Ekman dredge is designed to close after impacting the riverbed, and is only able to grab mud, sand, and gravel. Cobble or bedrock was implied from the lack of bed material in the dredge after a sample. Substrate material was categorized through a basic classification method defined by a gravelometer substrate template representing four categories (cobble/bedrock, gravel, sand, and silt/mud). Photographic evidence of the bed material collected in the dredge for each site was taken in order to ensure accuracy of the written observations (Figure 6). A similar classification model has been utilized before to model substrate type on the seafloor (Barnhardt et al. 1998). Six sites providing inconsistent substrate samples between collections were omitted from the model to reduce error.

Substrate Classification Scheme for the James River

A statistical analysis of the substrate samples and associated hardness values for each sample site was conducted using an analysis of variance model test (ANOVA) (Schuenemeyer and Drew 2011). The ANOVA test showed that the ground truth dataset was statistically valid in grouping of substrate and associated hardness values. The results of the test's 95 % confidence boundaries were selected as the best-fit percent signal return values from the hardness data, representing the transition from one substrate type to another. Classification ranges were then adjusted to represent the full range of possible hardness values. Once the transition values were determined, the hardness map could then be reclassified as either a mud, sand, gravel or bedrock/cobble substrate. A classification map was developed from the substrate hardness map, which separated the four bottom habitat types based on hardness values and the transition values determined in the ANOVA test. The resulting substrate type classification map enabled quantification and visualization of the dominant substrate composition within the reach. Hard bottom habitat areas could be quantified by summing the gravel and cobble/bedrock areas within the reach.

Essential Habitat

The substrate type classification and depth maps were associated with existing knowledge of essential spawning habitat requirements for Atlantic sturgeon. Depth of known spawning sites outside of the James River range from 6 - 27 m, with most observations having occurred in water deeper than 10 m. The sites were often located in pools considerably deeper than the rest of the river (Leland 1968, Scott and Crossman 1973, Bain et al. 2000, Hatin et al. 2002). A depth restriction ≥ 10 m was used to further define hard bottom habitat areas that could potentially support sturgeon spawning success. Hard bottom portions in less than 10 m of water could potentially support spawning success, and depth restrictions should not be seen as a clearly defined variable restricting spawning success or failure. Bottom substrate is a critical parameter defining essential spawning habitat and if appropriate substrate is present, a range of secondary variables (such as shallow depths, temperature fluctuations, or low DO) may still support spawning (Bushnoe and Musick 2005).

Historical Analysis Methods

Historical sounding charts published in 1853 and 1880 were used to compare the change in substrate composition throughout the study area (NOAA 2012). The historical charts lacked the data density and accuracy of modern day sampling methods. Substrate hardness in the historical data was recorded as either sticky, soft, or hard (Figure 7) at regular intervals along with sounding depths. The bottom substrate classification map was further simplified to either hard (gravel and cobble/bedrock classes) or soft (mud and sand classes) bottom, enabling a comparative assesment of hard bottom coverage in 1853, 1880, and 2012. The 1853 historic maps were able to represent the full study area, and were compared to the 2012 bottom substrate classification map by dividing the study area into upper, middle, and lower sections (Richmond to Warwick ending at river buoy 166, Warwick to Hatcher Island ending at river buoy 150, and Hatcher Island to City Point ending at river buoy 121) (Figure 1). The 1880 maps only represented the river from Hatcher Island to City Point, and as such confined any comparision between the 1880 data and the 1853 or 2011 data to the lower portion of the study area.

The hard and soft bottom sounding percentages were calculated by georeferencing the historic maps with the upper, middle, and lower sections of the 2012 map and NOAA navigation charts. All point locations of hard or soft/sticky bottom were manually digitized, and the percent of total recorded hard or soft bottom soundings was calculated. This was done because the historic maps were not spatially accurate enough to create a representative substrate map. The percent of hard bottom soundings from 1853 and 1880 in each section was compared with the percent hard bottom for the 2012 dataset.

RESULTS

The investigation produced datasets for side scan imagery, bathymetry, bottom hardness, and ground truth substrate classification toward the delineation of essential sturgeon spawning habitat in the tidal freshwater reach of the James River. Side scan imagery was collected for the full extent of the study area. Bathymetry (depth) and bottom hardness were mapped (Figures 8 and 9) for 9.43 km^2 of river. Raw depth data indicated an average 200 kHz sample depth of 6.1 m. The downward facing beam projects a 20 degree sonar cone, which at the average sample depth of 6.1 m, would sample approximately 1.2 m^2 of river bottom during a single sonar pulse, indicating approximately 0.5 km^2 of the 9.4 km^2 (approximately 5 %) hardness map was raw data. Depths ranged from 1 to 22 m, and the average depth for the entire reach was 4.2 m. Bottom hardness, represented by the distribution of the interpolated signal return strength, was skewed towards the lower return values. Approximately 84 % of the hardness values for the reach were below a signal return strength of 43 %, whereas 67 % of the distribution was below a signal strength of 35 % (Figure 10). The analysis of variance test verified the signal return strength ranges associated with substrates from the ground truth sampling sites to be significantly distinct ($F = < 0.0001$) (Tables 1 and 2, Figure 11). However, the Tukey test showed that gravel and sand were not statistically different from each other ($p = 0.1361$, $\alpha = 0.05$). Nonetheless, 95 % confidence limits were used to create a classification scheme that represented the continuous range of hardness values possible (Table 3). Mud (signal return 1-35 %) represented 67 % of the river bottom area, sand (signal return 36-43 %) represented 17 %, gravel (signal return 44-53 %) represented 11 %, and bedrock (signal return 54-100 %) represented 5 % of the bottom area (Figures 12 and 13). Approximately 16 % of the study area (approximately 1.5 km^2) was gravel or cobble/bedrock hard-bottom habitat.

Hard bottom habitat was predominantly located in the middle and lower portion of the study area. The upper reach contained 1 % hard bottom habitat, covering only 0.02 km^2 of river bottom. The middle reach contained 26 % hard bottom habitat covering approximately 0.67 km^2. The lower reach contained approximately 15 % hard bottom habitat, representing 0.81 km^2 of river bottom. The largest area of continuous hard bottom habitat is approximately 0.25 km^2 and was found in the Jones Neck shipping channel cut. Large stretches of hard bottom habitat can also be found around the Turkey Island channel cut (0.22 km^2), around buoy number 137 (0.15 km^2), around the 295 bridge at buoy number 150 (0.22 km^2), buoy number 160 (0.08 km^2), around the power plant at buoy number 154 (0.11 km^2), and around Kingsland Reach near buoy number 156 (0.14 km^2). Approximately 0.22 km^2 (2 %) of all hard bottom habitat was found within the narrow shipping channel cuts past the Turkey and Jones Neck Islands. Selecting for hard bottom locations $\geq$ 10 m deep generated a map describing essential spawning locations within the study area (Figure 14), and concluded the study area contained 0.7 km^2 essential spawning habitat.

Historical Analysis of Hard Bottom Substrate

Current river bottom morphology and depth were strongly influenced by channel modification and dredging for the majority of the reach. Large discrepancies in raw depth readings compared to the only available NOAA navigation charts (1969) indicated significant substrate deposition has occurred within the Jones Neck and Turkey Island oxbows in recent years. Based on the historical sounding data, the tidal freshwater reach of the James River contained 40 % hard bottom habitat in 1853 versus 16 % in 2012 (Figure 15). The river was further assessed based on the upper, middle, and lower sections as defined by the available historic maps (Figure 7). The upper section, between Richmond and Warwick, had 56 % hard bottom in 1853 compared to 1 % hard bottom in 2012, and experienced the most change (55 % hard bottom loss) (Figures 15 and 16). The middle section, between Warwick and Hatcher Island, had 38 % hard bottom in 1853 compared to 26 % hard bottom in 2012, experiencing the least loss of hard bottom habitat for the study area (12 %). The lower section, between Hatcher Island and City Point, had 28 % hard bottom in 1853 compared to 15 % hard bottom in 2012, and experienced a similar hard bottom habitat loss (13 %). A slight increase in hard bottom habitat is described between 1853 and 1880 in the lower portion of the reach, especially around the Jones Neck oxbow (31 % to 44 % hard bottom) (Figure 18), but the lower portion of the study area experienced an overall loss of habitat between 1880 and 2012 (44 % to 19 %, respectively). The tidal freshwater portion of the James River has undergone a loss of 24 % of its historic hard bottom habitat between 1853 and 2012. Between 1880 and 2012, the middle and lower portions of the study area experienced an overall loss of 25 % of its historic hard bottom habitat, indicating that the James River has lost a large percentage of the historic hard bottom habitat.

DISCUSSION

The hardness values from the substrate ANOVA 95 % confidence range used to define gravel and sand classes overlapped by approximately 2 %, and was adjusted for in the model by assuming the middle value of the difference as the most likely transition point between the two categories (Table 2 and 3). A statistically significant difference between sand and gravel was observed at a 85 % confidence interval ($\alpha = 0.15$), The difference between the 85 % and 95 % confidence intervals was only 1 %, and as such did not significantly affect our model. Observational data from ground truth samples indicated substrate composition is not typically uniform or segregated like the classification model suggests and is often comprised of a mix of substrates (i.e. gravel/sand mixture). Substrate size and level of compaction also influenced the associated hardness value, where a more compact sand substrate would reflect a slightly stronger sonar signal than a loosely packed sand substrate (Pelin 2011). Ground truth samples for sand and gravel often noted a mix of both substrates, which likely explains the lack of statistical difference between sand and gravel at $\alpha = 0.05$.

Natural bends in the river have favored the creation and preservation of hard bottom habitat. Large areas of consistent hard bottom habitat were found to be located near most major bends in the study area. The correlation between location of hard bottom habitat and the presence of a river bend is likely due to the nature of river dynamics, where the outside of bends in the river are typically influenced by scouring generated by suspended material and fluvial forces within the river (Holton and Walsh 1995). Outside of the bends, the fluvial forces seem to promote a sediment free environment ideal for sturgeon egg survival. The large areas of hard bottom habitat are found within relatively deep water compared to the average river depth and may prove to be favorable for sturgeon spawning success (Leland 1968, Scott and Crossman 1973). Future investigation of the large hard bottom regions may provide valuable information for fisheries managers in relation to the protection of naturally occurring hard bottom habitat in the river for spawning purposes. Modern day dredging activities have likely preserved, uncovered, or created new hard bottom habitat at depths below the 10 m threshold throughout the reach, and may partially protect the viability of the hard river bottom for future spawning events in specific sections of the river.

The historical analysis identified a large change in dominant substrate types after the creation of the Hatcher, Jones Neck, and Turkey Island man-made cuts. Water velocities through the oxbows have been seemingly reduced from historic velocities due to a disproportional redirection of flow from the natural meanders into the comparatively narrow navigation cuts. The redirection of flow past the natural oxbows has favored increased sediment deposition in the oxbows, covering the region in silt and mud. Substantial reductions in water depths were observed in the oxbows when compared to current NOAA navigation charts last updated in 1969. Small regions of natural hard bottom still exist in the oxbows, typically located along the northern shoreline of the oxbows in select areas, but the vast majority of historic natural hard bottom habitat in the oxbows has been covered with a thick mud deposit.

The historical comparison also leads to the conclusion that anthropogenic sources have significantly altered the bottom substrate throughout the reach. Downstream of the fall line, the James River experiences tidal forces for the first time and as such may be naturally susceptible to depositional forces during an incoming tide, especially while carrying a high sediment load (Holton and Walsh 1995). The most striking observation pertains to the upper portion of the study area from Richmond to Warwick, which experienced the most significant loss of hard bottom habitat. The upper section of study area above the Richmond shipping terminal no longer seems to be maintained by dredging activities and has lost most of its historical hard bottom habitat (Holton and Walsh 1995). Observed rocky substrate in the upper portion of the study area seemed to have significant silt and sand deposits, and would not support the survival of sturgeon eggs deposited in the region. All three sections of the study area indicated a general loss of hard bottom habitat, supporting the hypothesis that the tidal freshwater James River has experienced a significant loss of exposed hard bottom substrate critical to sturgeon spawning success. The loss of natural hard bottom habitat in the study area was partially offset by the creation of hard bottom habitat found in the Turkey Island and Jones Neck cuts. The narrow man-made cuts around Jones Neck and Turkey Island experience apparent bottom scouring as the outgoing tide enters the narrow cuts. The highest (and thus hardest bottom) hardness values for the reach are found in the Turkey Island cut, and similarly high return values are associated with the Jones Neck cut. The channel cuts are of particular interest in relation to sturgeon spawning as there is an increased risk of ship strikes within the narrow cuts (Balazik et al. 2012, Brown and Murphy 2010). As such, fisheries managers could use the essential habitat model to better regulate shipping activity past large hard bottom locations during a fall or spring spawn.

The slight increase in hard bottom habitat between 1853 and 1880 in the lower portions of the study area may be due to a multitude of factors such as post-Civil War economic changes reducing anthropogenic sources (limited development, farming etc.), different survey personnel or methodology, or simply sampling bias on behalf of the historic data collection team.

Existing knowledge related to sturgeon spawning habitat is limited and generally indicates sturgeon favor hard bottom habitat in relatively deep waters compared to surrounding depths (Sulak et al. 2000). Confining the hard bottom to depths ≥ 10 m isolated hard bottom areas to a depth comparable to spawning sturgeon observations in the Hudson, Delaware, and St Lawrence River systems. The depth restricted model was based on observations of spawning sturgeon outside of the James River system and as such is not a clearly defined variable determining spawning success within the James River itself.

Temperature was not monitored in the study. Thermal effluent released from a local power plant may potentially influence spawning viability in the section of river around buoy number 154 (Niklitschek and Secor 2005). Thermal releases would require constant monitoring in order to accurately account for the full impact of a thermal plume during a spawning season. Sturgeon are often seen well upstream of the thermal plume, and as such the presence of thermal effluent does not seem to be a significant deterrent for spawning sturgeon. The influence of the thermal plume on eggs attached to substrate within the plume is unknown. Further investigation into the potential impact of thermal stress on sturgeon spawning in the James may prove insightful in understanding the recovery potential of Atlantic sturgeon in the James River.

The overall loss of historic hard bottom habitat has likely limited sturgeon recovery rates in the region. The reduced hard bottom habitat across the study area limits the availability of essential spawning habitat to specific locations in the river system. Sturgeon recovery in the James River is still viable, as significant portions of river bottom are dominated by hard bottom habitat in the middle and lower portions of the study area. The return of Atlantic sturgeon to the James River every fall and spring supports the conclusion that Atlantic sturgeon are still able to locate and spawn over suitable habitat within the James River system. Protection of the remaining hard bottom habitat within the tidal freshwater portion of the river is critical for spawning success and should be considered a restoration priority.

The identification and comparison of the remaining essential hard bottom habitat can enable fisheries managers better understand and protect areas essential for Atlantic sturgeon spawning success. Repeating a substrate analysis in future studies may provide a more detailed understanding of how quickly the river bottom substrate is still changing, and if modern day remediation efforts have influenced the amount of hard bottom substrate in the reach.

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Table 1. Summary of ground truth substrate samples and associated percent signal return (hardness) for ground truth locations used in the statistical analysis. Five sample sites were omitted from the final analysis due to inconclusive sample returns at the sites.

	Substrate Samples				
Site #	#1	#2	#3	Conclusion	Avg. Signal Return
49926	mud	mud	mud	mud	12
76375	mud	mud	-	mud	16
97453	mud/sand	mud/silt		mud	17
89984	mud	mud	-	mud	25
30882	mud	mud	-	mud	26
35_1	sand	sand	-	sand	33
35_3	mud	cobble	mud	mud	33
35_5	mud	mud	-	mud	33
35_4	mud	mud	mud with some gravel	mud	34
35_2	mud	mud	-	mud	34
21757	sand/mud/organic	sand/mud	-	sand	35
40_4	sand	sand	-	sand	36
37136	bedrock/organic	mud	mud	mud	37
94185	mud	mud	-	mud	37
24599	sand	bedrock	sand/silt	sand	37
40_2	sand/debris	sand	-	sand	37
40_1	sand	sand	-	sand	38
40_3	sand	sand	-	sand	38
40_5	mud	mud	-	mud	38
52782	sand/pebbles	sand	-	pebble	41
45_5	bedrock	large gravel	sand/cobble	pebble	42
45_3	sandy mud	sandy mud	-	sand	43
45_2	sand	sand	-	sand	43
45_1	muddy debris	sand	sand	sand	43
56961	sand	sand	-	sand	44
45_4	sand	sand	-	sand	44
92546	sand/bedrock	sand/bedrock	-	sand	47
28207	bedrock	sand/pebble	cobble/pebble	pebble	47
38069	sand/organic	sand	-	sand	47
50_2	debris/sand	cobble	-	sand	47
45636	sand	sand/bedrock	sand/pebbles	gravel	48
50_1	sand	sand	-	sand	48
50_4	gravel	gravel/mud	-	gravel	48
24784	bedrock	sand/bedrock	bedrock	bedrock	49
55_3	large gravel	bedrock/gravel	-	gravel	52
77244	bedrock/little sand	bedrock/little sand	-	bedrock	53
55_4	pebble/cobble	bedrock	-	bedrock	53
55_5	bedrock	bedrock	-	bedrock	53
55_2	bedrock/large gravel	bedrock/gravel	-	gravel	53
55_1	gravel	sand/gravel	large gravel, maybe cobble	gravel	54
69941	bedrock	bedrock	-	bedrock	55
46943	mud	mud	-	mud*	61
63240	sand/silt	sand/bedrock	gravel/bedrock	bedrock	65
61907	bedrock	sed. bedrock	sedimentary bedrock	bedrock	67
37954	gravel	bedrock	gravel/bedrock	bedrock	76

Table 2. Summary of statistical analysis related to the substrate ground truth sampling of 44 different sites.

Mean Signal Return Strength for Oneway Anova

Classification	Number	Mean	Std Error	Lower 95%	Upper 95%
Bedrock	8	58.875	2.5321	53.757	63.993
Gravel	8	48.125	2.5321	43.007	53.243
Mud	12	28.5	2.0675	24.321	32.679
Sand	16	41.25	1.7905	37.631	44.869

Analysis of Variance

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**	**Prob > F**
category	3	4771.9773	1590.66	31.0108	<.0001
Error	40	2051.75	51.29		
C. Total	43	6823.7273			

Summary of Fit

Rsquare	0.699321
Adj Rsquare	0.67677
Root Mean Square Error	7.161966
Mean of Response	42.22727
Observations (or Sum Wgts)	44

Table 3. Final classification of side scan sonar percent return signal strength ranges for each substrate type.

	Signal Return Strength Range	
Substrate Classification	**Low**	**High**
mud	1%	35%
Sand	36%	43%
Gravel	44%	53%
Bedrock/Cobble	54%	100%

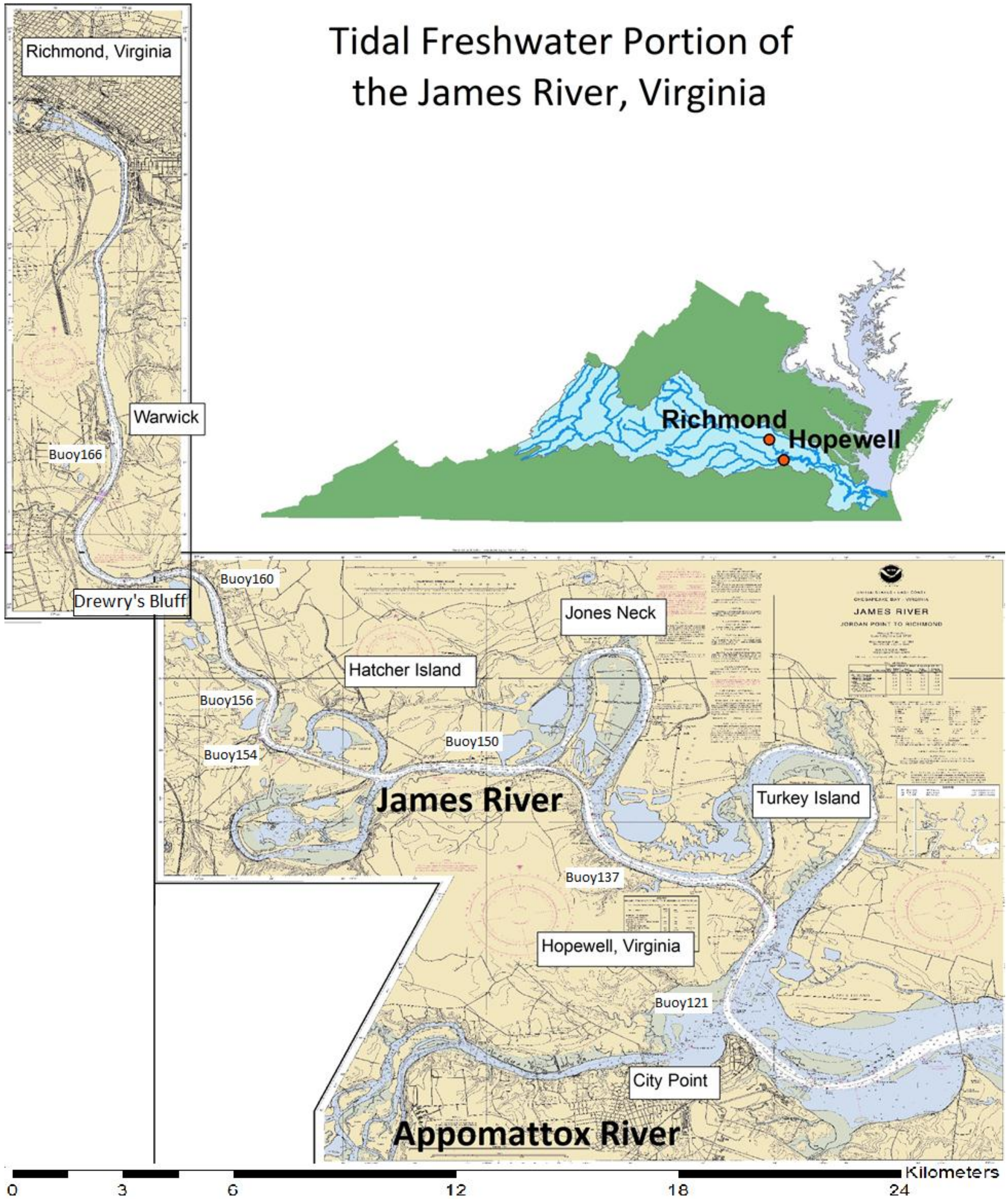

Figure 1. Map describing the extent of the study area from Richmond, Virginia, to the mouth of the Appomattox River, near City Point and Hopewell, Virginia. Points of interest in this study have also been included for reference.

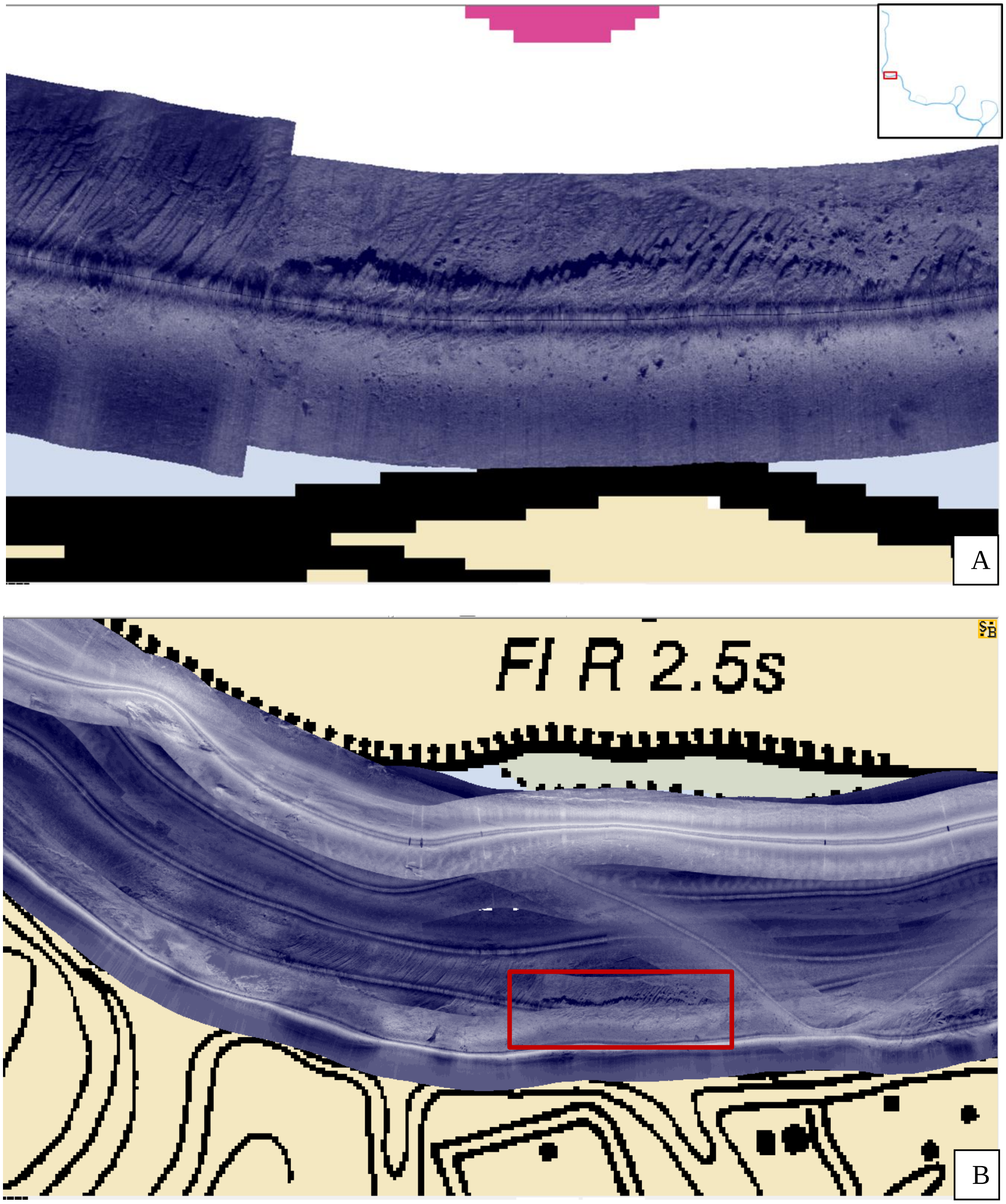

Figure 2. An example of sidescan imagery from a single boat pass in Dr. Depth (A). Imagery was later combined in Dr. Depth and brought into arcmap in order to create a complete image of the river bottom for the entire reach (B). The dark strip down the middle of the image is a result of removing the water column from the image, and thus represents the boat track.

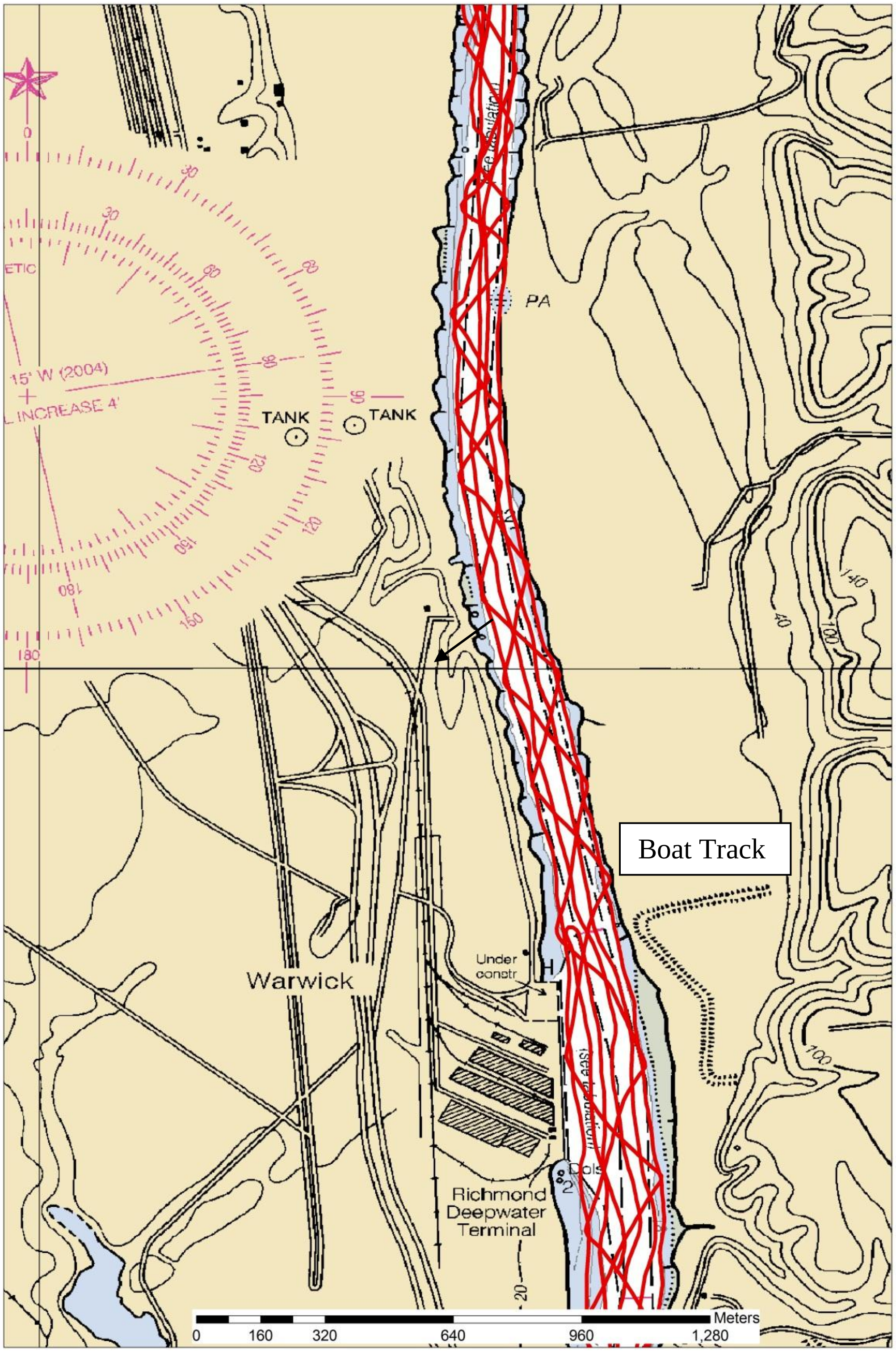

Figure 3. The basic sampling pattern visualized as raw depth/hardness data before interpolation.

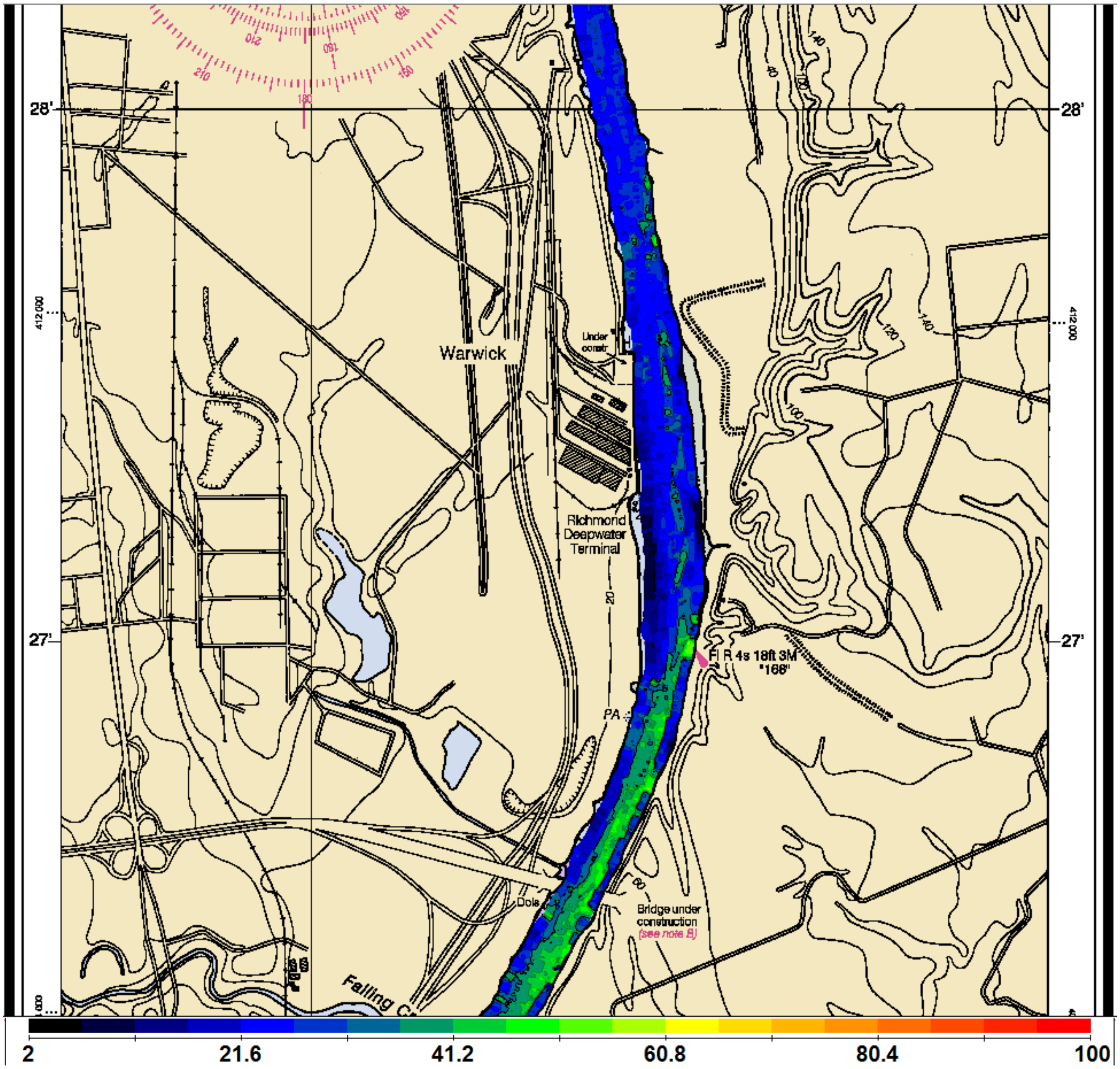

Figure 4. Interpolated hardness data describing the percent signal return from the 200 kHz downward facing sonar beam. Hardness interpolation extended no further than 25 meters out from the raw data.

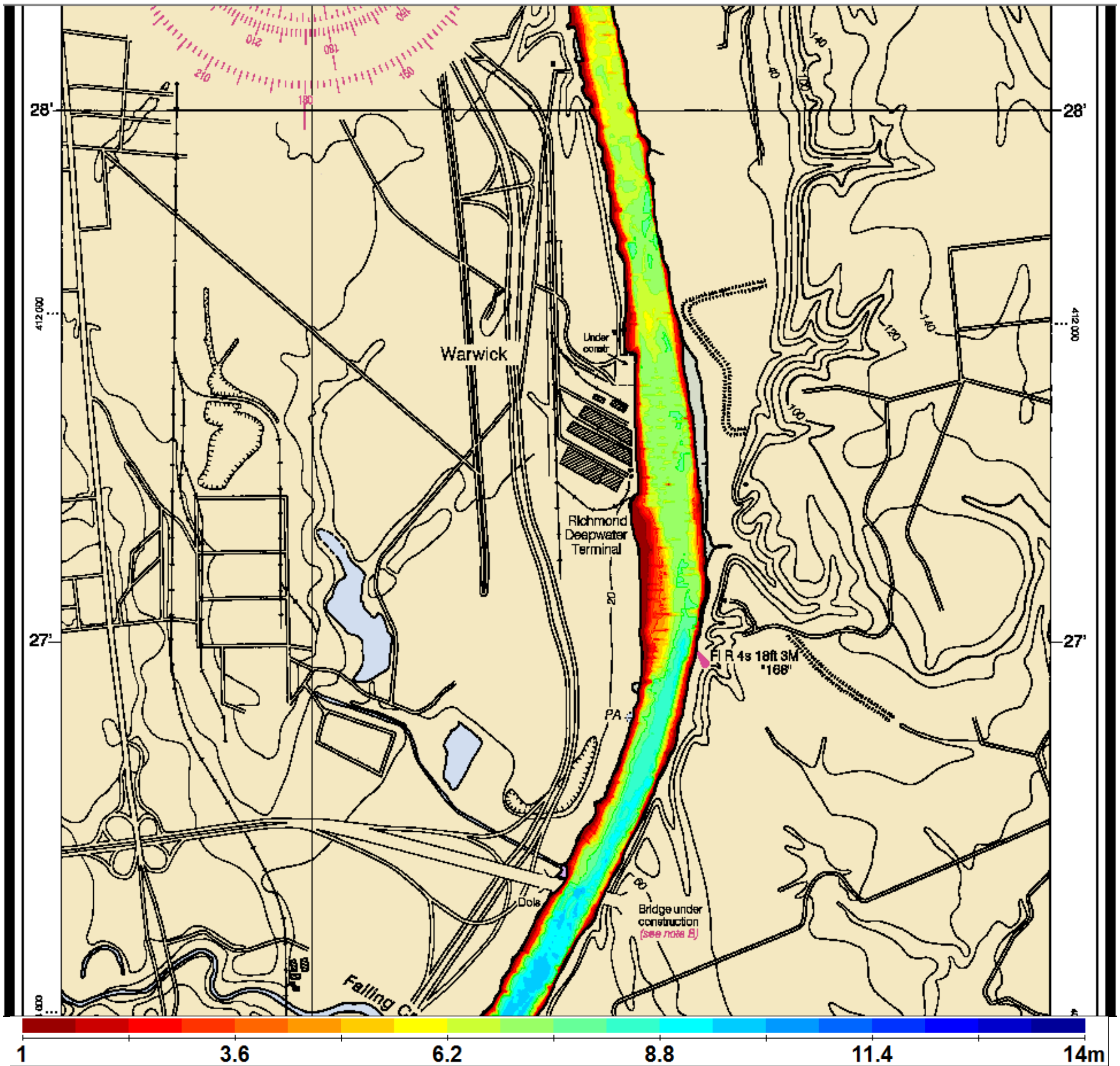

Figure 5. Interpolated depth data describing the full river width in Dr. Depth. The interpolation was done for all data within the reach no further than 25m out from the raw data and no further than 50 m out in shallow waters.

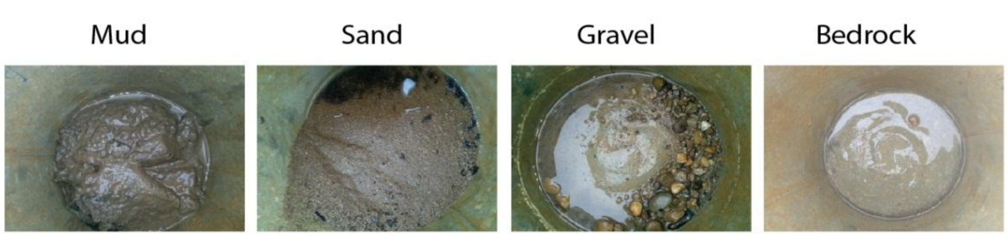

Figure 6. Photographs of typical bed material collected during ground truth sampling for each classification type. Bedrock/cobble was characterized by the general lack of substrate (Photographs of substrate in bottom of a bucket).

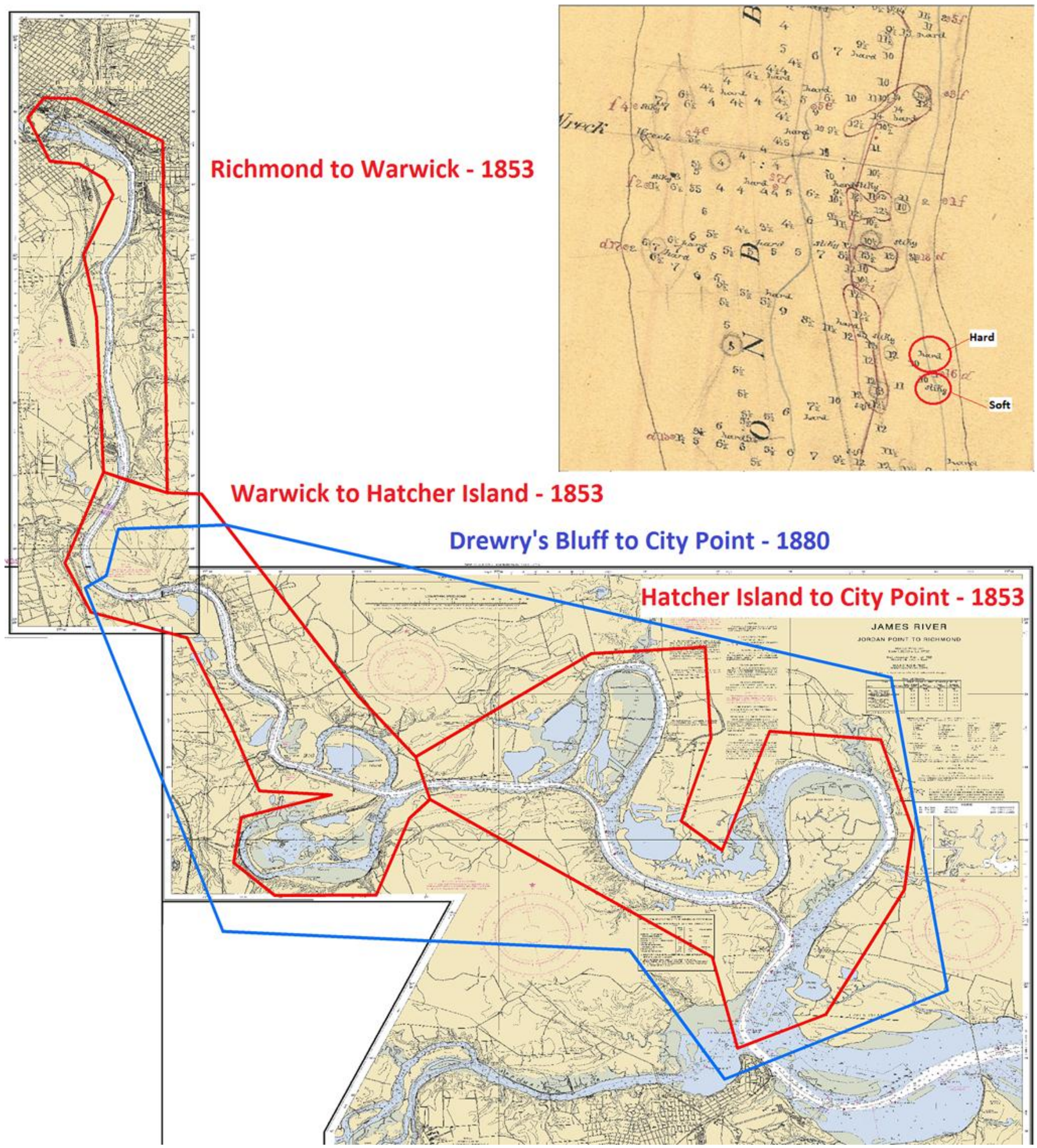

Figure 7. Map describing the coverage of the 1853 and 1880 sounding charts used in the historical analysis (NOAA 2012). Hard and sticky labels were used in the historic maps to describe bed hardness.

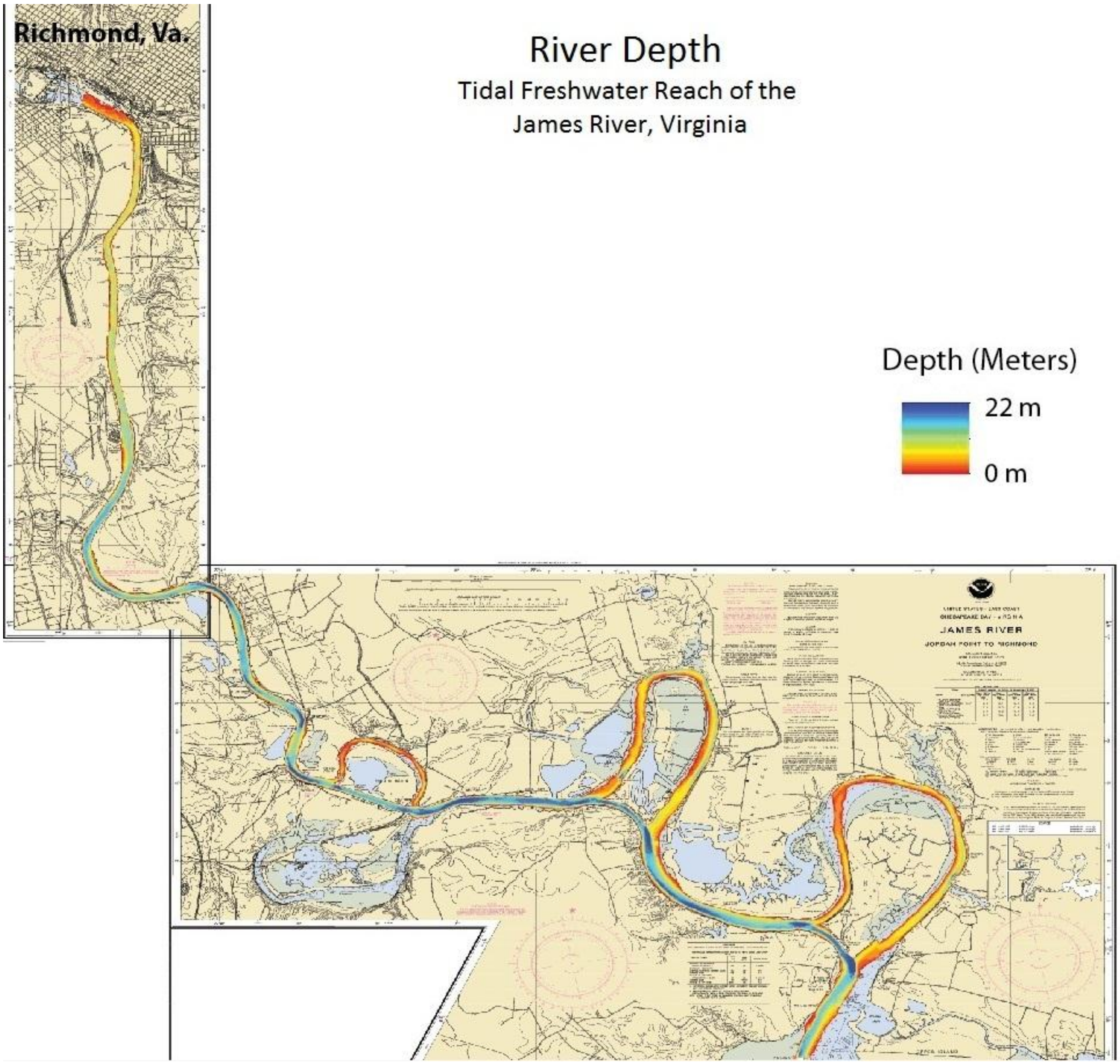

Figure 8. The complete depth chart generated in Dr. Depth and further processed in Arcmap describing the depth fluctuations for the study area. Data was applied over a local NOAA navigation chart.

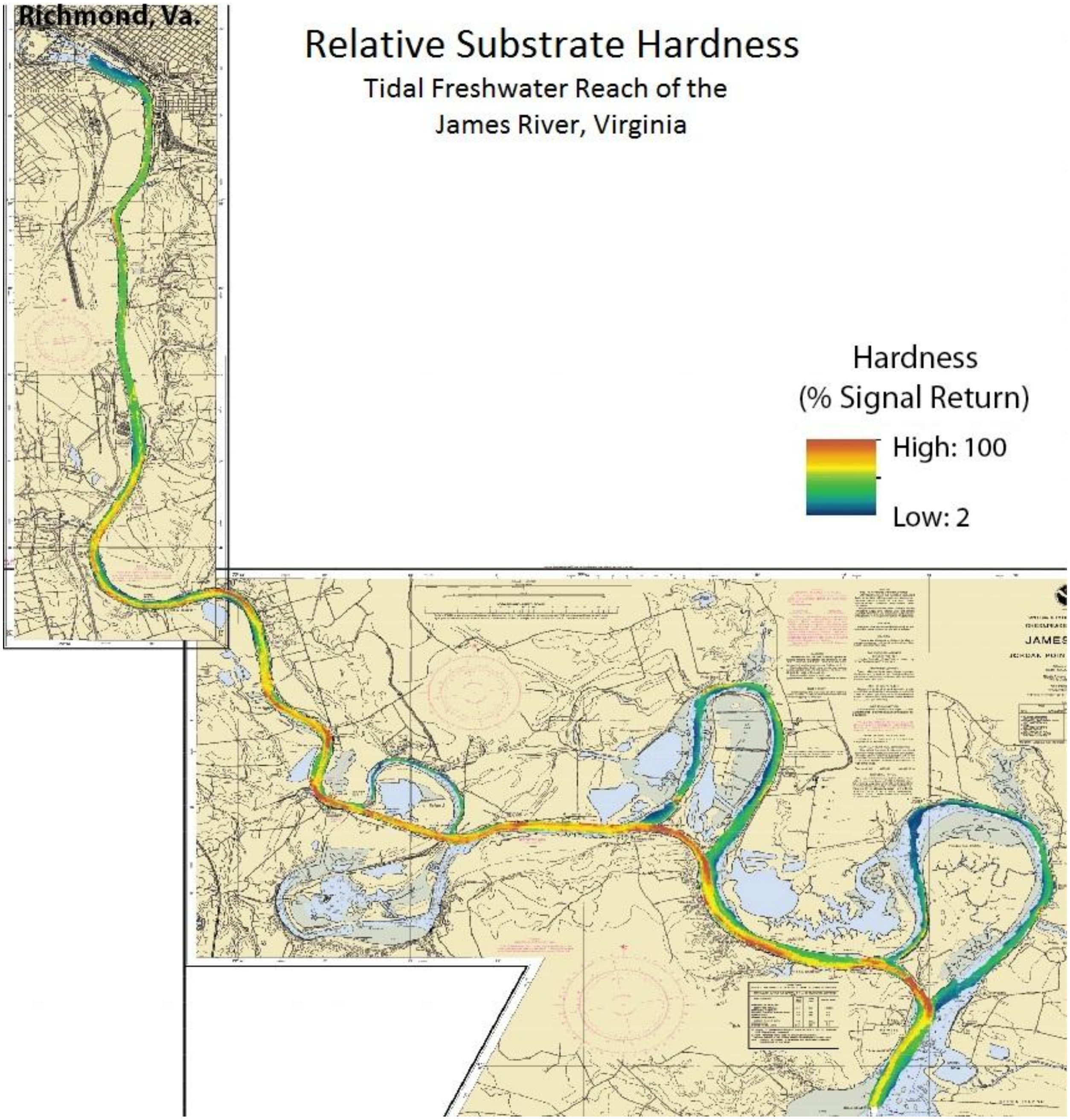

Figure 9. The complete relative hardness map describing the percent signal return of the 200 kHz sonar beam throughout the reach. A higher return was indicative of a hard bed materal. As such, a higher return would typically imply a substrate such as gravel, cobble or bedrock, whereas a weak return would imply a soft material such as sand, mud, or silt.

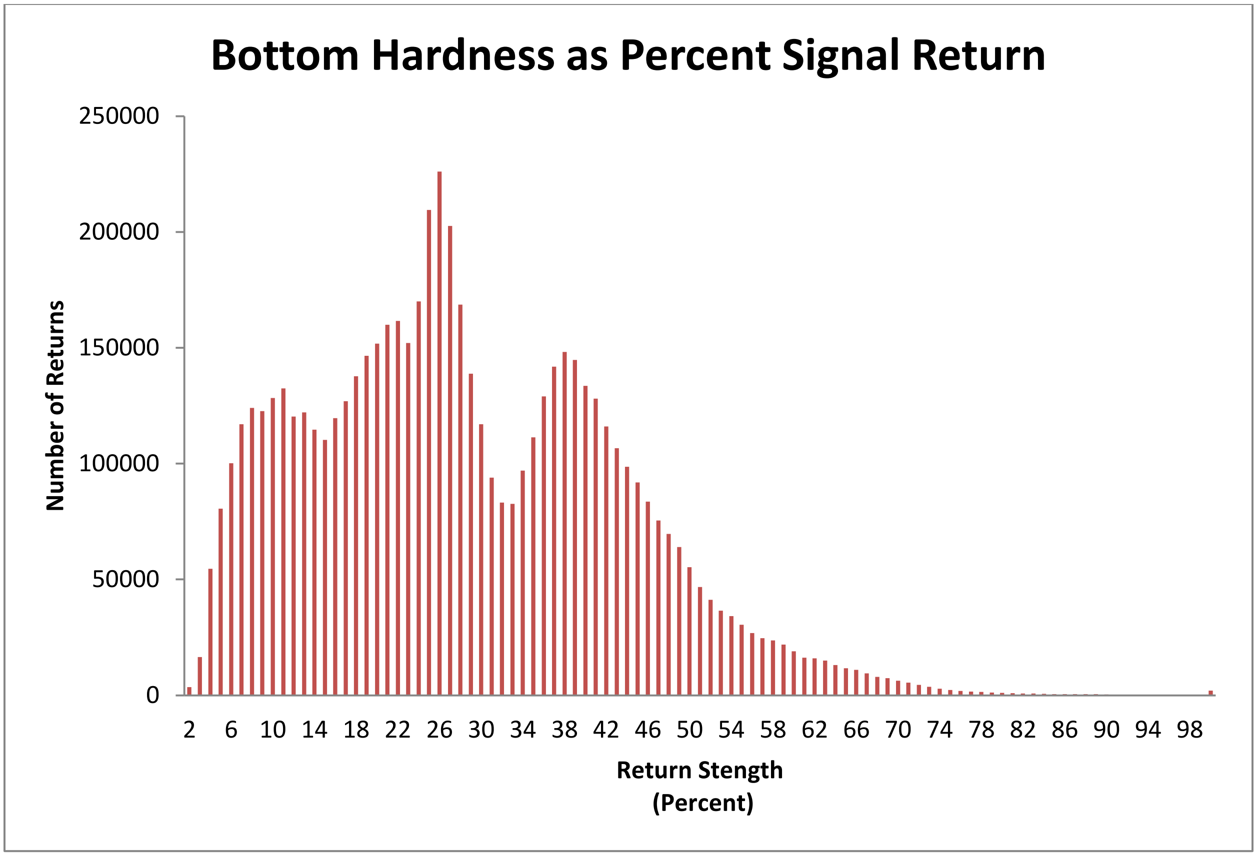

Figure 10. Chart describing the raw distribution of signal returns for the entire reach.

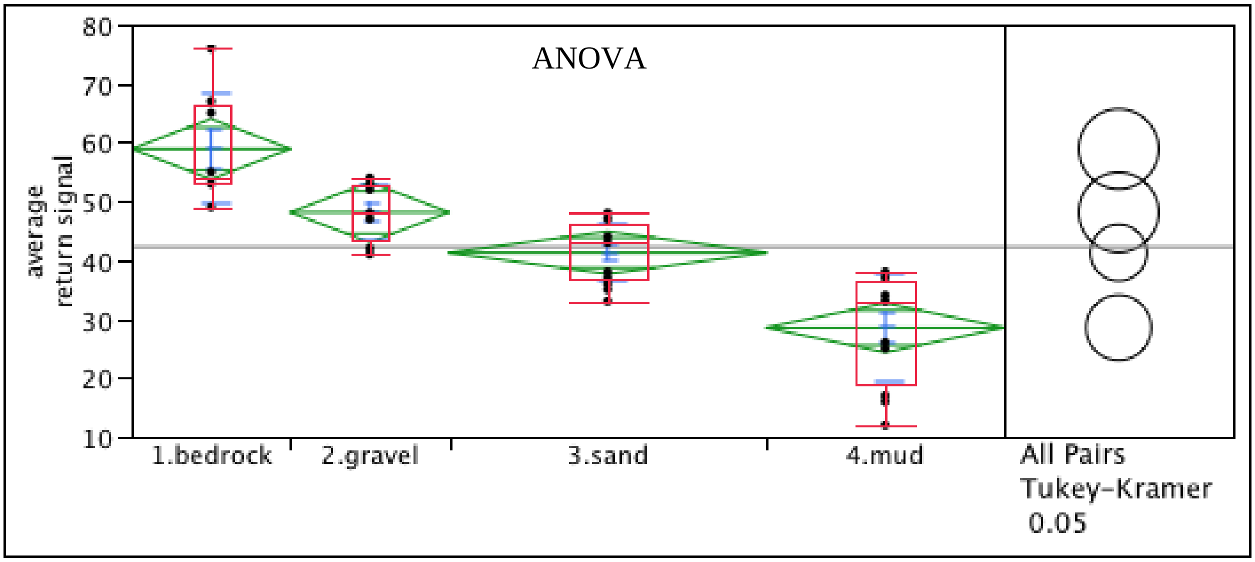

Figure 11. One way Anova and Tukey-Kramer test describing the distribution of return signal associated with ground truth sample type from across the reach.

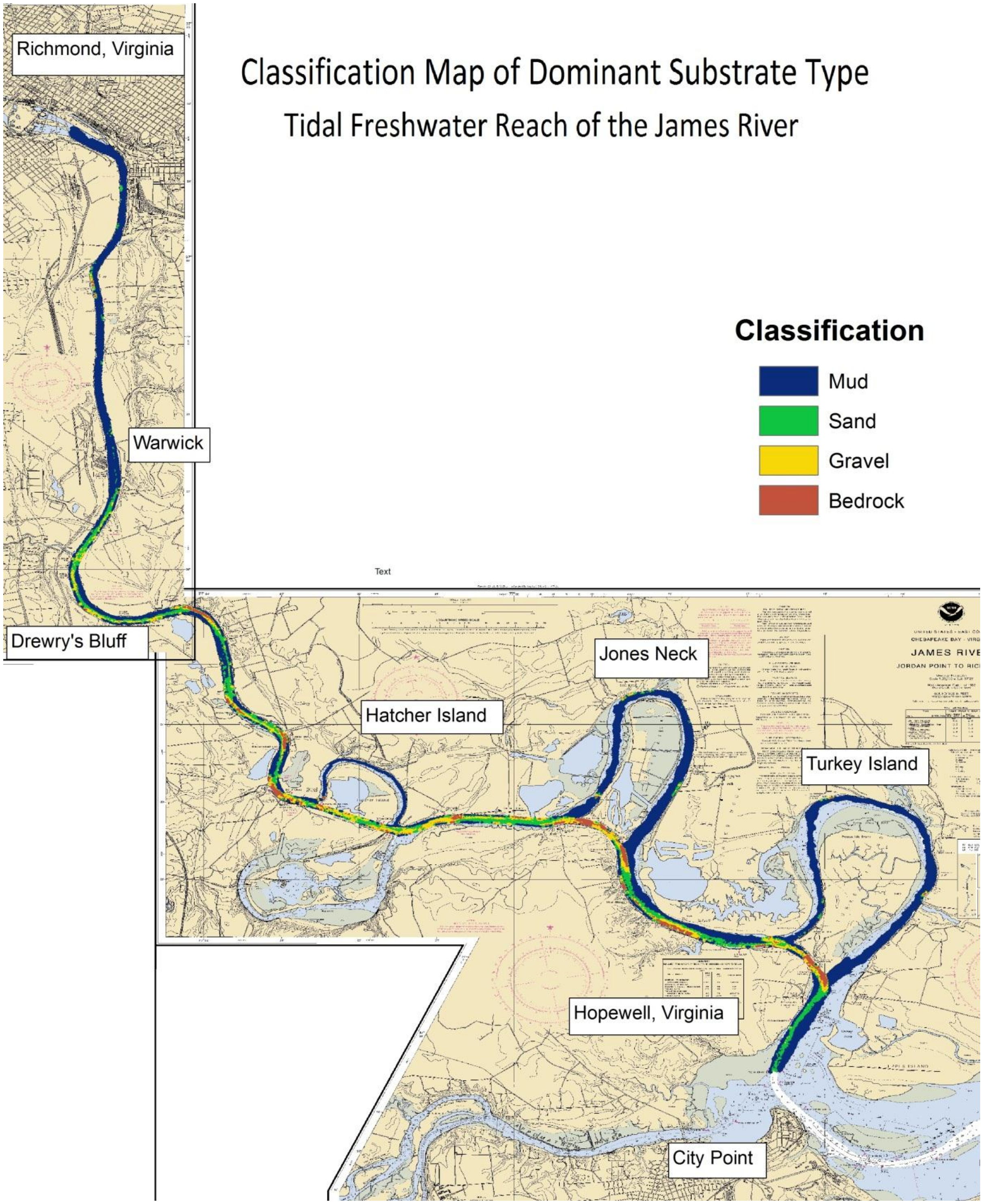

Figure 12. Map describing the dominant substrate within the reach based on the four classification types. Classification groups were determined from the statisitcal analysis of ground truth samples and 200 kHz hardness values.

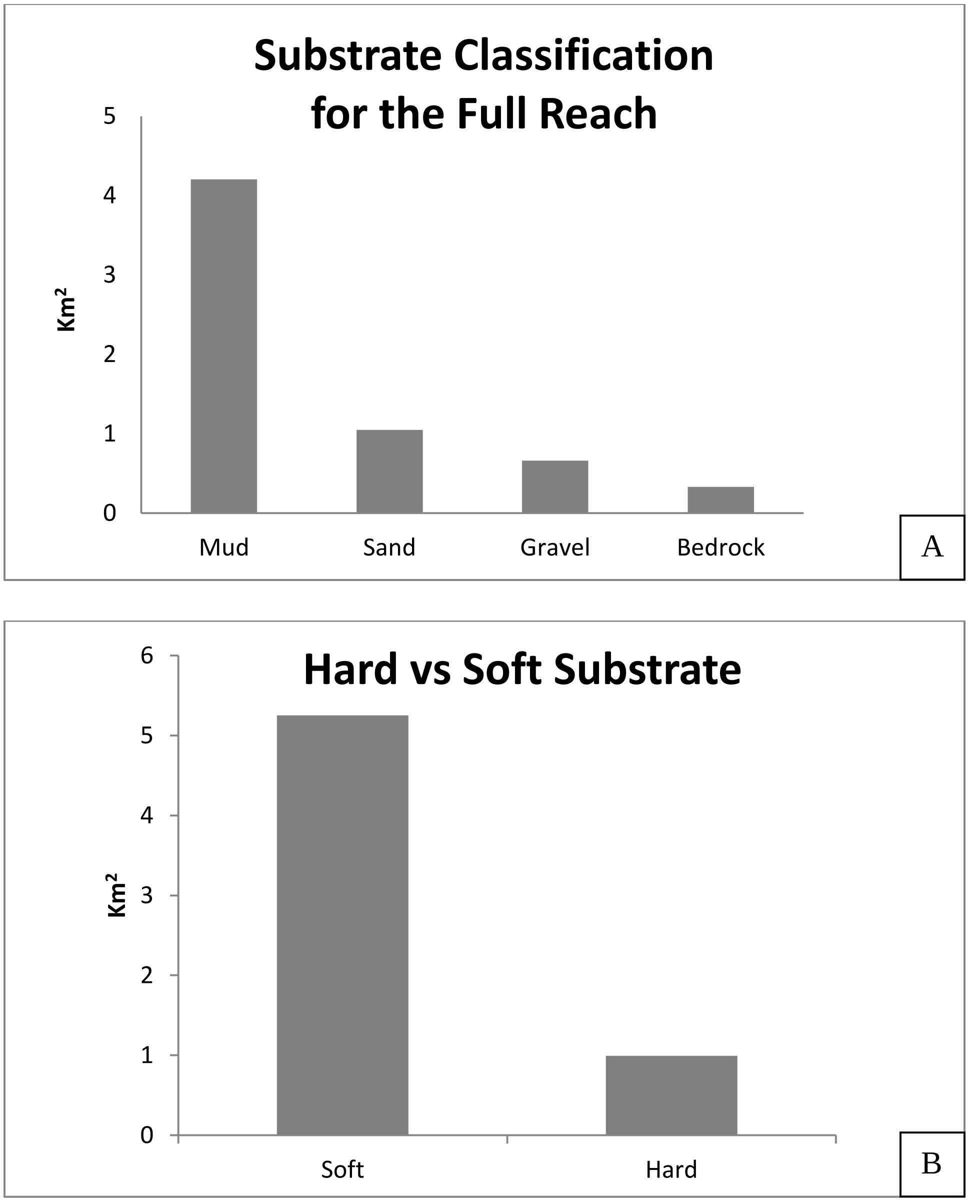

Figure 13. Chart describing the distribution of substrate classifications based on hardness values throughout the study area (A). Gravel and bedrock classifications were combined to represent the total available hard bottom substrate in the study area (B).

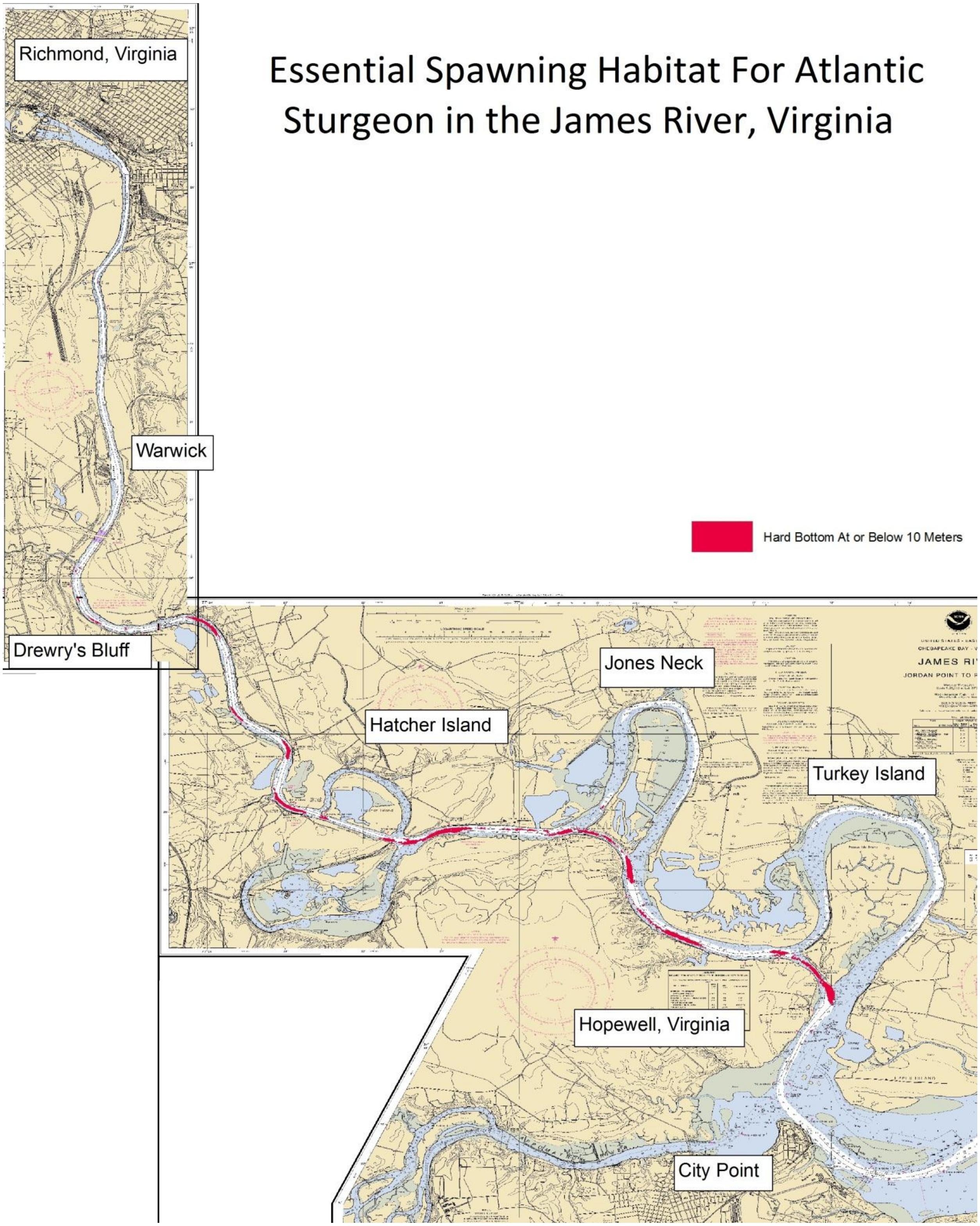

Figure 14: Map of the distribution of hard bottom habitat located where depth was ≥ 10 m.

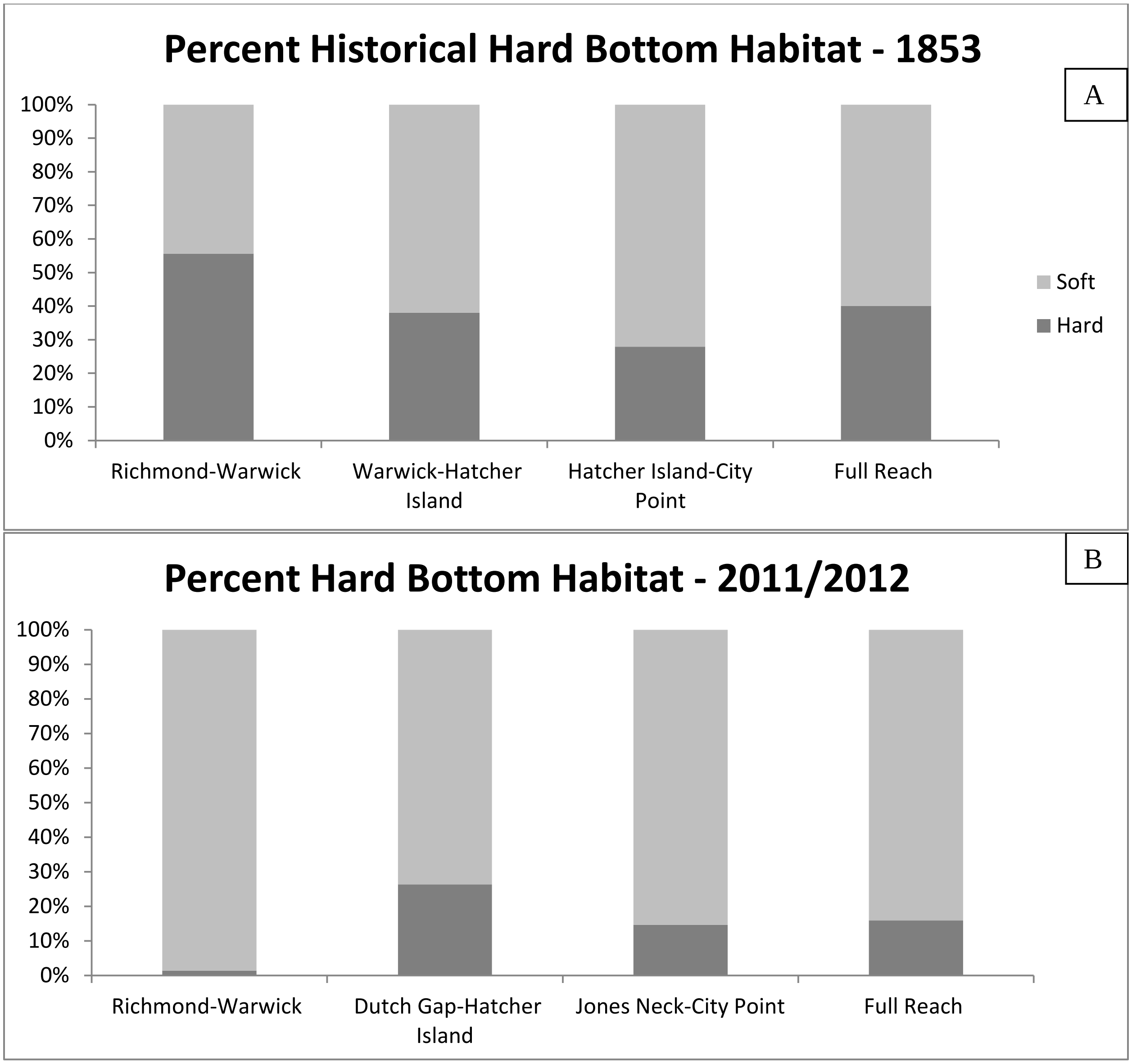

Figure 15. A comparision of percent hard bottom habitat for three sections of river between 1853 (A) and 2012 (B).

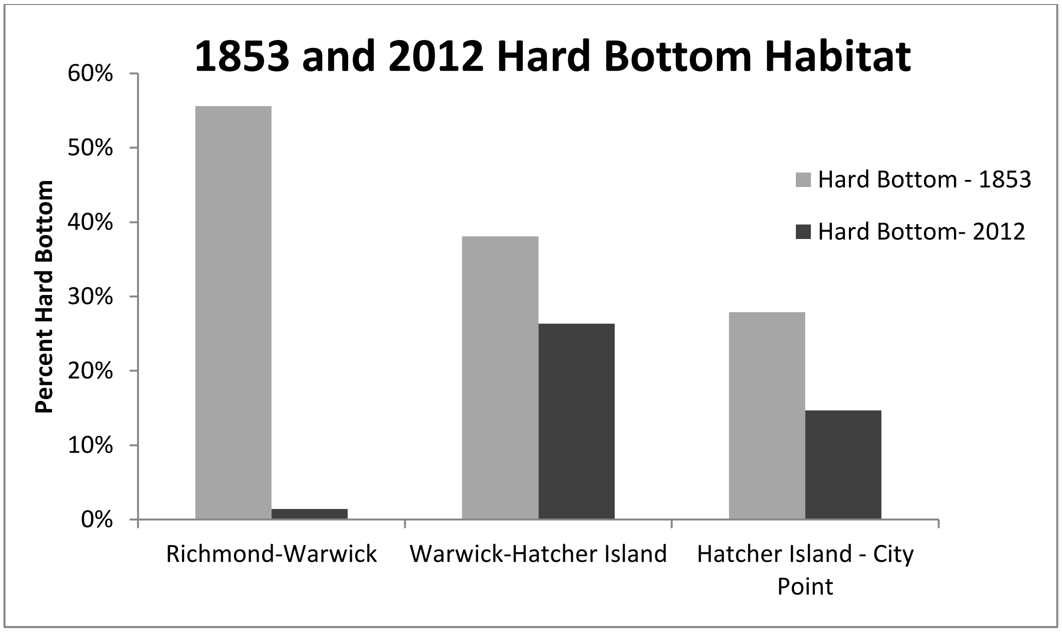

Figure 16. A comparison of hard bottom habitat for three sections of the reach for 1853 and 2012.

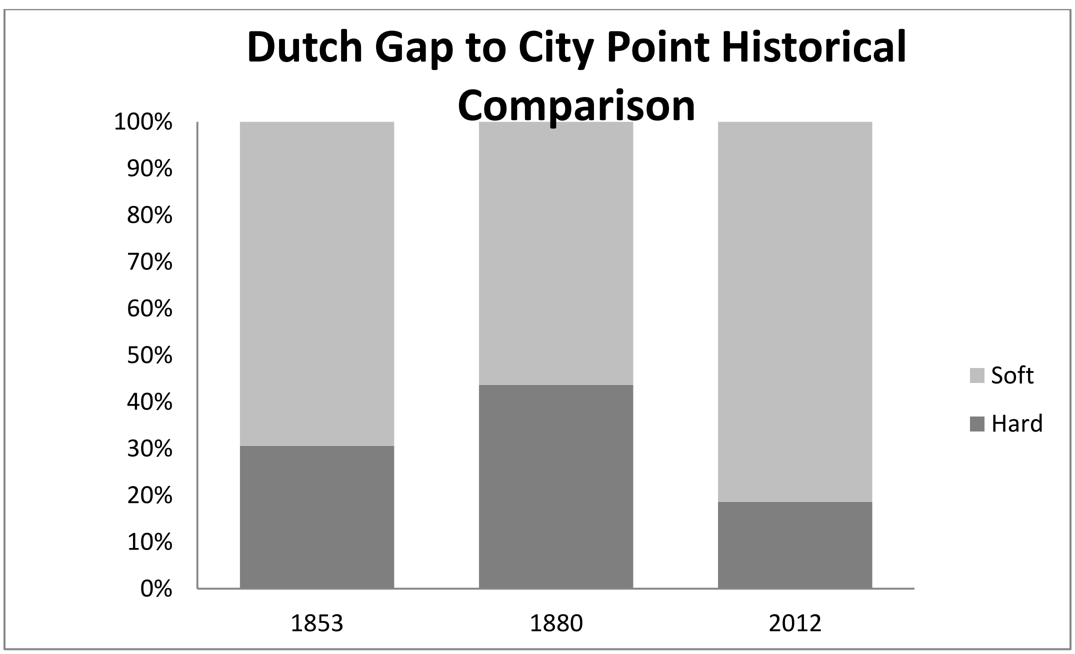

Figure 17. Comparison of the fluctuations in percent hard and soft bottom habitat for the lower two sections of river between Drewry's Bluff and City Point for 1853, 1880, and 2012.

VITA

Geoffrey Austin was born in Portsmouth, Virginia on September 18, 1987. After graduating from Stafford High School in 2006 he moved to Harrisonburg, VA where he received a B.S. though James Madison University as an Integrated Science and Technology major with a concentration in Environmental Studies. In 2010 he moved to Richmond, Virginia to pursue an M.S. in Environmental Studies through Virginia Commonwealth University (VCU). As a graduate student he was hired as a student employee through the USGS and worked in Dr. Greg Garman's VCU research lab where he assisted with several stream and river studies, of which include fish sampling and identification for VCU's INSTAR program, assisting with Richmond City water sampling, sturgeon gill netting, VCU catfish studies, and general research vessel operation. At the USGS, He assisted with surveying and hydro-acoustic modeling of river discharge for the main stem Shenandoah River Instream Flow Study. He also served as the lead technician for the Delaware River bathymetric survey side scan sonar ground truth work.